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CURRENT s - QUARK MASS CORRECTIONS TO THE FORM FACTORS OF D - MESON SEMILEPTONIC DECAYS

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Abstract

The infinite mass effective theory, when a heavy quark mass tends to infinity, and Chiral perturbation theory at the quark level, based on the extended Nambu – Jona – Lasinio model with linear realization of chiral $U(3)\times U(3)$ symmetry, are applied to the calculation of current s – quark mass corrections to the form factors of the $D \to \bar{K}\; e^+\; \nu_e$ and $D \to \bar{K}^*\; e^+\; \nu_e$ decays. These corrections turn out to be quite significant, of the order of $7-20\%$. The theoretical results are compared with experimental data.

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1 Introduction

In our recent publications [1,2] we calculated in the chiral limit the form factors of the semileptonic $D \to \bar{K}^{*} e^{+} \nu_e$ and $D \to \bar{K} e^{+} \nu_e$ decays. For the description of D-mesons we applied the infinite mass effective theory (IMET) [3,4], when the c-quark mass M_c tends to infinity, i.e. $M_c \to \infty$. In IMET the long – distance physics we describe within Chiral perturbation theory at the quark level $(\mathrm{CHPT})_q$ [5], based on the extended Nambu – Jona – Lasinio (ENJL) model with linear realization of chiral $U(3) \times U(3)$ symmetry [6].

In this paper we apply IMET and $(\mathrm{CHPT})_q$ to the calculation of the fine structure of the form factors of the $D \to \bar{K} e^{+} \nu_e$ and $D \to \bar{K}^{*} e^{+} \nu_e$ decays at the first order in current s – quark mass expansion. Within IMET and $(\mathrm{CHPT})_q$ the first order current – quark – mass corrections to the mass spectra of charmed pseudoscalar and vector mesons and charmed pseudoscalar – meson leptonic constants have been calculated in [7]. The amplitude of the $D \to h\, e^{+} \nu_e$ decay can be determined as follows

$$M\,(D \to h\,e^{+}\nu_e) = -\frac{G_F}{\sqrt{2}} V^{*}_{cs} < h\,(Q)|\bar{s}\,(0)\,\gamma_\mu\,(1 - \gamma^5)\,c\,(0)|D\,(p) > \ell^{\mu}\,, \qquad (1)$$

where $h = \bar{K}$ or $\bar{K}^{*}$, $G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$ is Fermi weak constant, $|V_{cs}| = 0.975$ is the CKM – mixing matrix element, $s(0)$ and $c(0)$ are the s – and c – current quark fields with N colour degrees of freedom each, and $\ell^{\mu} = \bar{u}\,(k_{\nu_e})\,\gamma^{\mu}\,(1 - \gamma^5)\,v\,(k_{e^+})$ is the weak leptonic current.

We shall seek the hadronic matrix element

$$M_\mu\,(D \to h) = < h\,(Q)|\bar{s}\,(0)\,\gamma_\mu\,(1 - \gamma^5)\,c\,(0)|D\,(p) > \qquad (2)$$

in the form of an expansion in powers of the current s – quark mass upto first order terms

$$M_\mu\,(D \to h) = M^{(0)}_\mu\,(D \to h) + M^{(1)}_\mu\,,(D \to h). \qquad (3)$$

Here we have denoted

$$M^{(0)}_\mu\,(D \to h) = < h\,(Q)|\bar{s}\,(0)\,\gamma_\mu\,(1 - \gamma^5)\,c\,(0)|D\,(p) >_{\mathrm{ch.l.}} \qquad (4)$$

$$\begin{aligned} M^{(1)}_\mu\,(D \to h) &= \\ &= -\,i\,m_{0\,s} \int d^4x\, < h\,(Q)|T(\,\bar{s}\,(x)\,s\,(x)\,\bar{s}\,(0)\,\gamma_\mu\,(1 - \gamma^5)\,c\,(0))|D\,(p) >_{\mathrm{ch.l.}}\,. \end{aligned} \qquad (5)$$

The matrix element $M^{(0)}_\mu\,(D \to h)$ describes the $D \to h$ transition calculated in the chiral limit (ch.l.) while $M^{(1)}_\mu\,(D \to h)$ is the first order correction in the current s – quark mass expansion. The matrix elements $M^{(0)}_\mu\,(D \to h)$ for $h = \bar{K}^{*}$ and $\bar{K}$ have been calculated in [1,2]. In this paper we shall calculate $M^{(1)}_\mu\,(D \to h)$.

In accordance to the procedure expounded in [1,2,7] we reduce (5) to the expression

$$\begin{aligned} M^{(1)}_\mu\,(D \to h) &= g_D\,m_{0\,s}\,i \int d^4x\,, \int_{-\infty}^{\infty} d\,z_0\,\theta\,(-\,z_0\,) \times \\ &\times < h\,(Q)|T(\,\bar{s}\,(x)\,s\,(x)\,s(0)\,\gamma_\mu \left(\frac{1 + \gamma^0}{2}\right) \gamma^5\,q\,(z_0, \vec{0}\,))|0 >_{\mathrm{ch.l.}} \end{aligned} \qquad (6)$$

obtained in leading order in the large N and M_c expansion, $q = u$ or d for D^0 or D^+, respectively. The coupling constant g_D has been calculated in [8]

$$g_D = \frac{2\sqrt{2}\,\pi}{\sqrt{N}}\left(\frac{M_D^2}{M_c\,\bar{v}'}\right)^{1/2}, \tag{7}$$

where $\bar{v}' = 4\Lambda = 2.66$ GeV and Λ is the cut – off in 3 – dimensional Euclidean momentum space. Λ is connected to the scale of spontaneous breaking of chiral symmetry (SBCS) Λ_χ by the relation $\Lambda = \Lambda_\chi/\sqrt{2} = 0.66$ GeV at $\Lambda_\chi = 0.94$ GeV [5].

The r.h.s. of (6) involves only the light – quark fields. Therefore for the evaluation of (6) we can apply $(\mathrm{CHPT})_q$ [5,7]. Since the leading order of the r.h.s. of (6) in current – quark – mass expansion is fixed by the factor m_{0s}, so the matrix element $< h(Q)|\,T(\ldots)\,|0>$ has to be calculated in the chiral limit (ch.l.).

By applying the formulas of quark conversion (Ivanov [5]) we can present the matrix element $M^{(1)}_\mu(D \to h)$ in terms of constituent – quark – loop diagrams [7]. The momentum representation of these diagrams reads

$$\begin{aligned} M^{(1)}_\mu(D \to h) &= i\,m_{0s}\,g_D\,g_h\,\frac{\bar{v}}{4m}\left(-\frac{N}{16\pi^2}\right)\int\frac{d^4k}{\pi^2 i}\,\mathrm{tr}\Big[\frac{1}{m-\hat{k}}\,\Gamma_h\,\times \\ &\times\frac{1}{m-\hat{Q}-\hat{k}}\,\frac{1}{m-\hat{Q}-\hat{k}}\,\gamma_\mu(1-\gamma^5)\left(\frac{1+\hat{v}}{2}\right)\gamma^5\,\frac{1}{k\cdot v+i0}\Big]. \end{aligned} \tag{8}$$

The appearance of the factor $\bar{v}/4m$ is due to the contribution of the diagram with the light scalar σ_s – meson exchange [8]. Here $\bar{v} = -<0|\bar{q}q|0>/F_0^2 = 1.92$ GeV, $F_0 = 0.092$ GeV and $m = 0.33$ GeV are the PCAC constant of light pseudoscalar mesons and the constituent quark mass calculated in the chiral limit [5]. The coupling constants g_h describe the interaction between light constituent quarks and light mesons $\bar{K}$ and $\bar{K}^*$, that is $g_{\bar{K}} = 2\pi/\sqrt{N}$ and $g_{\bar{K}^*} = \pi\sqrt{6}/\sqrt{N}$ [7,8] such that $g_{\bar{K}^*}/g_{\bar{K}} = \sqrt{3/2}$ [5]. Γ_h is either $\Gamma_{\bar{K}} = i\gamma^5$ or $\Gamma_{\bar{K}^*} = \gamma_\nu\,e^{*\nu}(Q)$ depending on whether $h = \bar{K}$ or $h = \bar{K}^*$. Now we can proceed to the calculation of the current s – quark mass corrections to the form factors.

2 The $D \to \bar{K}\,e^+\nu_e$ decay

For the $D \to \bar{K}$ the matrix element $M^{(1)}_\mu(D \to \bar{K})$ reads

$$\begin{aligned} M^{(1)}_\mu(D \to \bar{K}) &= i\,m_{0s}\,g_D\,\frac{2\pi}{\sqrt{N}}\,\frac{\bar{v}}{4m}\left(-\frac{N}{16\pi^2}\right)\int\frac{d^4k}{\pi^2 i}\,\mathrm{tr}\Big[\frac{1}{m-\hat{k}}\,i\gamma^5\,\times \\ &\times\frac{1}{m-\hat{Q}-\hat{k}}\,\frac{1}{m-\hat{Q}-\hat{k}}\,\gamma_\mu(1-\gamma^5)\left(\frac{1+\hat{v}}{2}\right)\gamma^5\,\frac{1}{k\cdot v+i0}\Big] = \\ &= m_{0s}\,g_D\,\frac{\sqrt{N}}{4\pi}\int\frac{d^4k}{\pi^2 i}\,\frac{k_\mu}{[m^2-k^2-i0][m^2-(k+Q)^2-i0]}\,\frac{1}{k\cdot v+i0} + \\ &+ \ldots. \end{aligned} \tag{9}$$

Following [9,10] we have kept only divergent contributions. The dots denote the contributions of convergent integrals. The integration over k gives [1]

$$
\begin{aligned}
&\int \frac{d^4k}{\pi^2\, i}\, \frac{k_\mu}{[\,m^2 - k^2 - i\,0\,]\,[\,m^2 - (k+Q)^2 - i\,0\,]}\, \frac{1}{k\cdot v + i\,0} = \\
&= v_\mu\, 2\,\ell n\left(1 + \frac{\bar v\,'}{4\,Q_0}\right) + Q_\mu\, \frac{2}{Q_0}\Big[\,1 - \ell n\left(1 + \frac{\bar v\,'}{4\,Q_0}\right)\Big]
\end{aligned}
\tag{10}
$$

where $Q_0 = (M_D^2 - q^2)/2\,M_D$ is the energy of the massless K – meson in the rest frame of the D – meson. The appearance of the q^2 – dependence is due to the q^2 – dependence of Q_0. The matrix element $M^{(1)}_\mu(D \to \bar K)$ can be expressed in terms of two form factors

$$
M^{(1)}_\mu(D \to \bar K) = f^{(1)}_+(q^2)\,(p + Q)_\mu + f^{(1)}_-(q^2)\;,(p - Q)_\mu
\tag{11}
$$

where

$$
\begin{aligned}
f^{(1)}_+(q^2) &= \frac{m_{0\,s}}{M_*}\,\frac{\bar v}{4\,m}\,\frac{M_D^2}{M_D^2 - q^2}\Big[\,1 - \frac{M_D^2 + q^2}{2\,M_D^2}\,\ell n\left(1 + \frac{M_*^2}{M_D^2 - q^2}\right)\Big]\,,\\
f^{(1)}_-(q^2) &= -\frac{m_{0\,s}}{M_*}\,\frac{\bar v}{4\,m}\,\frac{M_D^2}{M_D^2 - q^2}\Big[\,1 - \frac{3\,M_D^2 - q^2}{2\,M_D^2}\,\ell n\left(1 + \frac{M_*^2}{M_D^2 - q^2}\right)\Big]\,.
\end{aligned}
\tag{12}
$$

Here we have denoted $2\,M_* = \sqrt{2\,M_D\,\bar v\,'}$. It should be stressed that the formulae (12) are valid in the physical region only, i.e. $0 \le q^2 \le (M_D - m_K)^2$. At $q^2 = 0$ the form factors $f^{(1)}_+(0)$ and $f^{(1)}_-(0)$ read

$$
\begin{aligned}
f^{(1)}_+(0) &= \frac{m_{0\,s}}{M_*}\,\frac{\bar v}{4\,m}\Big[\,1 - \frac{1}{2}\,\ell n\left(1 + \frac{M_*^2}{M_D^2}\right)\Big] = 0.09\,,\\
f^{(1)}_-(0) &= -\frac{m_{0\,s}}{M_*}\,\frac{\bar v}{4\,m}\Big[\,1 - \frac{3}{2}\,\ell n\left(1 + \frac{M_*^2}{M_D^2}\right)\Big] = -0.02\,.
\end{aligned}
\tag{13}
$$

In the chiral limit the quantity $f_+(0)$ has been calculated in [8] (see also [2])

$$
f^{(0)}_+(0) = \frac{1}{\sqrt{2}}\left(\frac{\bar v\,'}{2\,M_c}\right)^{1/2} = 0.6\,.
\tag{14}
$$

The numerical value is estimated at the equality $M_c = M_D = 1.86$ GeV accepted in our approach [9]. By adding the current s – quark mass correction (13) we get the total value of $f_+(0)$

$$
f_+(0) = f^{(0)}_+(0) + f^{(1)}_+(0) = 0.69
\tag{15}
$$

which is good compared with the experimental data $|f_+(0)|_{\rm exp} = 0.7 \pm 0.1$ [11]. Our result $f_+(0) = 0.69$ agrees well with the theoretical prediction by Dominguez and Paver [12] obtained within the QCD sum rule approach. We find the current s-quark mass correction to be about 15%.

3 The $D \to \bar{K}^* e^+ \nu_e$ decay

The matrix element $M^{(1)}_\mu (D \to \bar{K}^*)$ can be expressed in terms of four form factors [1]

$$\begin{aligned} M^{(1)}_\mu (D \to \bar{K}^*) &= i\, a^{(1)}_1 (q^2)\, e^*_\mu (Q^2) - i\, a^{(1)}_2 (q^2)\, (e^* (Q) \cdot p)\, (p + Q)_\mu - \\ &- i\, a^{(1)}_3 (q^2)\, (e^* (Q) \cdot p)\, (p - Q)_\mu - \\ &- 2\, b^{(1)} (q^2)\, \varepsilon_{\mu\nu\alpha\beta}\, e^{t\nu} (Q)\, p^\alpha Q^\beta ,\ (\varepsilon^{0123} = 1). \end{aligned} \tag{16}$$

In order to obtain the form factors $a^{(1)}_i (q^2)$ $(i = 1, 2, 3)$ and $b^{(1)} (q^2)$ we have to calculate the following momentum integral

$$\begin{aligned} \mathcal{M}_{\mu\nu} &= \int \frac{d^4 k}{\pi^2 i} \mathrm{tr} \Big[\frac{1}{m - \hat{k}} \gamma_\nu \frac{1}{m - \hat{Q} - \hat{k}} \frac{1}{m - \hat{Q} - \hat{k}} \times \\ &\times \gamma_\mu (1 - \gamma^5) \left(\frac{1 + \hat{v}}{2} \right) \gamma^5 \frac{1}{k \cdot v + i\, 0} \Big] . \end{aligned} \tag{17}$$

By keeping only divergent contributions [9,10] and using the integrals given in the Appendix of [1], we get

$$\begin{aligned} \mathcal{M}_{\mu\nu} = &- 4\, \ell n \left(\frac{\bar{v}'}{4\, m} \right) g_{\mu\nu} + \frac{8}{M^2_D - q^2} \Big[1 - \ell n \left(1 + \frac{M^2_*}{M^2_D - q^2} \right) \Big] Q_\mu p_\nu - \\ &- \frac{8\, i}{M^2_D - q^2} \Big[1 - \ell n \left(1 + \frac{M^2_*}{M^2_D - q^2} \right) \Big] \varepsilon_{\mu\nu\alpha\beta}\, p^\alpha Q^\beta . \end{aligned} \tag{18}$$

The appearance of the q^2 – dependence is due to the quantity $Q_0 = (M^2_D - q^2)/2\, M_D$, being the energy of the massless $\bar{K}^*$ – meson in the rest frame of the D – meson. The neglect of the $\bar{K}^*$ – meson mass in the r.h.s. of (17) is in accordance with the prescription of $(\mathrm{CHPT})_q$ which incorporates the Vector Dominance approach [5,13], admitting the smooth dependence of low – energy hadronic matrix elements on the masses of low –lying vector mesons $(\rho, \omega, \varphi, K^*)$ [1,13,14].

By using (18), one can calculate the following chiral corrections to the form factors of the $D \to \bar{K}^*$ transition

$$\begin{aligned} a^{(1)}_1 (q^2) &= \frac{\sqrt{3}}{2} \frac{m_{0s}}{M_*} \frac{\bar{v}}{4\, m} M_D\, \ell n \left(\frac{\bar{v}'}{4\, m} \right) \\ a^{(1)}_2 (q^2) &= - a^{(1)}_3 (q^2) = b^{(1)} (q^2) \\ b^{(1)} (q^2) &= \frac{\sqrt{3}}{2} \frac{m_{0s}}{M_*} \frac{\bar{v}}{4\, m} \frac{M_D}{M^2_D - q^2} \Big[1 - \ell n \left(1 + \frac{M^2_*}{M^2_D - q^2} \right) \Big] . \end{aligned} \tag{19}$$

In the chiral limit the form factors of the $D \to \bar{K}^*$ transition have been calculated in [1]

$$
\begin{aligned}
a_1^{(0)}(q^2) &= \sqrt{\frac{3}{8}}\, M_* \\
a_2^{(0)}(q^2) &= \sqrt{\frac{3}{8}}\, \frac{M_*}{M_D^2}\Big[\frac{q^2}{M_D^2 - q^2} + \\
&+ \frac{M_D^2 - q^2}{M_*^2}\left(1 - \frac{2\, m\, M_D}{M_D^2 - q^2}\right) \ell n \left(1 + \frac{M_*^2}{M_D^2 - q^2}\right)\Big]\,, \\
a_3^{(0)}(q^2) &= -\sqrt{\frac{3}{8}}\, \frac{M_*}{M_D^2}\Big[\frac{2\, M_D^2 - q^2}{M_D^2 - q^2} - \\
&- \frac{M_D^2 - q^2}{M_*^2}\left(1 - \frac{2\, m\, M_D}{M_D^2 - q^2}\right) \ell n \left(1 + \frac{M_*^2}{M_D^2 - q^2}\right)\Big]\,, \\
b^{(0)}(q^2) &= \sqrt{\frac{3}{8}}\, \frac{1}{M_*}\, \ell n \left(1 + \frac{M_*^2}{M_D^2 - q^2}\right).
\end{aligned}
\tag{20}
$$

Here we have used the relation (14). The numerical values of the form factors at $q^2 = 0$ read

$$
\begin{aligned}
a_1(0) &= a_1^{(0)}(0) + a_1^{(1)}(0) = 0.96 + 0.14 = 1.10\,(\mathrm{GeV})\,, \\
a_2(0) &= a_2^{(0)}(0) + a_2^{(1)}(0) = 0.14 + 0.03 = 0.17\,(\mathrm{GeV})^{-1}\,, \\
a_3(0) &= a_3^{(0)}(0) + a_3^{(1)}(0) = -0.42 - 0.03 = -0.45\,(\mathrm{GeV})^{-1}\,, \\
b(0) &= b^{(0)}(0) + b^{(1)}(0) = 0.21 + 0.03 = 0.24\,(\mathrm{GeV})^{-1}\,.
\end{aligned}
\tag{21}
$$

One sees that the first order current s-quark mass mass corrections are between 7 and 20%. The form factors $a_i(q^2)$ $(i = 1, 2, 3)$ and $b(q^2)$ are connected with the standard form factors $A_i(q^2)$ $(i = 1, 2, 3)$ and $V(q^2)$ via the relations [1]

$$
\begin{aligned}
A_1(q^2) &= \frac{1}{M_D + M_{\bar{K}^*}} a_1(q^2)|_{q^2=0} = 0.40 \\
A_2(q^2) &= (M_D + M_{\bar{K}^*})\, a_2(q^2)|_{q^2=0} = 0.47 \\
A_3(q^2) &= (M_D + M_{\bar{K}^*})\, a_3(q^2)|_{q^2=0} = -1.24 \\
V(q^2) &= (M_D + M_{\bar{K}^*})\, b(q^2)|_{q^2=0} = 0.66\,,
\end{aligned}
\tag{22}
$$

where $M_{\bar{K}^*} = 0.89$ GeV is the mass of the $\bar{K}^*$ – meson [11]. The theoretical values compare reasonably with recent experimental data [15]

$$
\begin{aligned}
A_1(0)_{exp} &= 0.46 \pm 0.05 \pm 0.05\,, \\
A_2(0)_{exp} &= 0.38 \pm^{0.11}_{0.12} \pm 0.07\,, \\
V(0)_{exp} &= 0.92 \pm^{0.19}_{0.18} \pm 0.12\,.
\end{aligned}
\tag{23}
$$

These numerical results obtained by taking into account the first order current s – quark mass corrections confirm the results found in [1]. It is because in [1] we expressed the form factors of the $D \to \bar{K}^*$ transition in terms of the form factor of the $D \to \bar{K}$ transition $f_+(0)$. There for the numerical estimate we used the value $f_+(0) = 0.7$, which we obtained in present paper only at the first order in current s – quark mass

expansion (15). Recall that in the chiral limit we have $f_+(0) = 0.6$. This overlap of results underscores the self – consistency of the current s – quark mass corrections to the form factors of the transitions $D \to \bar{K}^*$ and $D \to \bar{K}$ calculated within IMET and $(\mathrm{CHPT})_q$.

4 Conclusion

We have applied IMET and $(\mathrm{CHPT})_q$ for the computation of the current s – quark mass corrections to the form factors of the semileptonic decays of the non – strange charmed D – mesons, $D \to \bar{K}\, e^+ \nu_e$ and $D \to \bar{K}^*\, e^+ \nu_e$. We have obtained non – zero contributions for the first order corrections in current s – quark mass expansion to the form factors of the $D \to \bar{K}\, e^+ \nu_e$ decays. This result contradicts the Ademollo – Gato theorem for the form factors of the semileptonic decays of K – mesons [16]. Within $(\mathrm{CHPT})_q$ the Ademollo – Gato theorem has been analyzed in [17]. The observed contradiction can be explained as an effect of IMET. Indeed IMET is based on the infinite limit $M_c \to \infty$ which violates chiral $SU(4) \times SU(4)$ symmetry, a necessary condition for the validity of the Ademollo – Gato theorem for the the $D \to \bar{K}\, e^+ \nu_e$ decays. The current s – quark mass corrections to the form factors of the $D \to \bar{K}^*\, e^+ \nu_e$ decays are consistent with the corrections calculated for the form factors of the $D \to \bar{K}\, e^+ \nu_e$ decays.

Note that we have kept to the first order corrections in current s – quark mass expansion calculated at the tree – meson level. Of course, the one – meson – loop corrections can be taken into account too. The consistent procedure for meson – loop chiral corrections within $(\mathrm{CHPT})_q$ has been developed in Ref.[5]). This procedure can also be applied to charmed meson physics.

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